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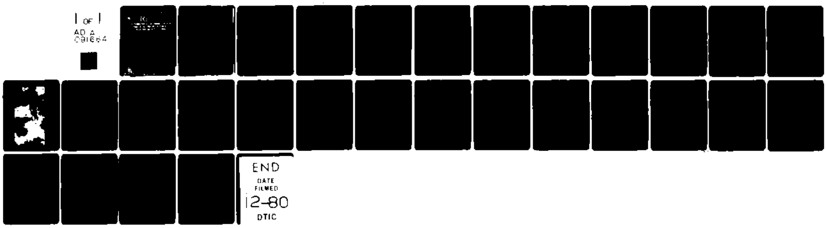

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DETERMINATION OF THE PRIMARY SPECULAR POINT IN THE SUNGLINT PATTERN OF A POLAR-ORBITING SATELLITE IMAGE

Ted L. Tsui and Robert W. Fett
Naval Environmental Prediction Research Facility

AUGUST 1980

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A mathematical procedure for calculating the location of the primary specular point (PSP) in polar-orbiting satellite data is described in step-by-step detail. For purposes of this discussion, the PSP is defined as "that point on the great circle arc perpendicular to the satellite subpoint track passing through the satellite subpoint and the solar subpoint where the angle of incidence of the sun's rays on a horizontal plane (measured from the local zenith) is equal to the angle of reflection of the sun's rays to the satellite

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20. ABSTRACT (Continued)

in space. The procedure can easily be developed into a small computer program that can be run on a minicomputer or on a programmable calculator.

CONTENTS

1. INTRODUCTION

The reflective effects of sunglint must be considered during interpretation of satellite imagery because these effects frequently can be mistaken for clouds. Under conditions of uniform seas, the central and most brilliant sunglint reflectance emanates from what is termed the "primary specular point (PSP)"; ability to determine this point's location is fundamentally important to a thorough analysis of satellite data.

In relation to polar-orbiting satellite data, Fett and Mitchell (1977) define the PSP as "that point on the great circle arc perpendicular to the satellite subpoint track passing through the satellite subpoint and the solar subpoint where the angle of incidence of the sun's rays on a horizontal plane (measured from the local zenith) is equal to the angle of reflection of the sun's rays to the satellite in space."

Fett and Mitchell (1977) describe a method for locating the PSP in Defense Meteorological Satellite Program (DMSP) data by a graphical procedure that utilizes gnomonic charts and developed nomograms. This present study develops a more accurate mathematical procedure that can be applied to several operative satellite systems and can be translated conveniently into a simple computer program for running on a minicomputer or programmable calculator.

2. THEORETICAL CONSIDERATIONS

The problem of determining the location of the PSP in polar-orbiting satellite data can be solved easily by spherical trigonometry if the satellite subpoint track is assumed to be a great circle. Though this assumption will lead to some errors in locating the PSP, the magnitude of the errors will be small enough to be acceptable for practical purposes.

Figure 1 shows the geometrical aspects of one of the typical problem situations. If the satellite subpoint track is considered as a great circle, the PSP (point Q in Figure 1) can be found by locating the point X first.

Step 1:

Find the position of X, which is the point on the satellite subpoint track intersected by the great circle arc perpendicular to the satellite subpoint track and passing through the sub-solar point (SSP).

Consider spherical triangle ZPO:

$OZ = 90°$

$ZP = 90°$ - solar declination angle

$\angle OZP$ = longitude of ascending node - longitude of SSP.

According to the laws of sines and cosines (Appendix I),

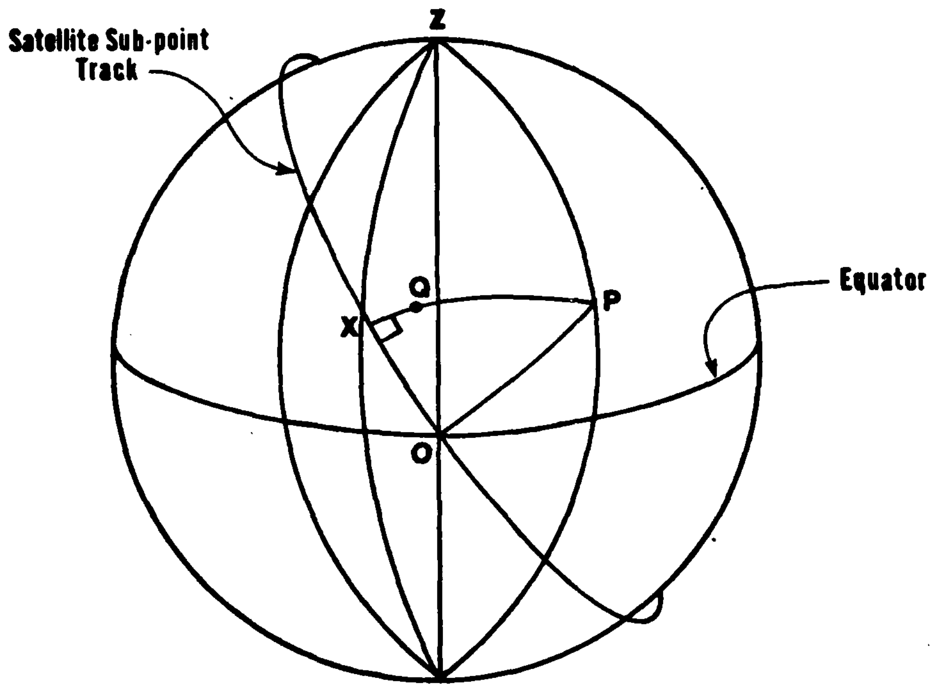
$$\cos PO = \cos OZ \cdot \cos ZP + \sin OZ \cdot \sin ZP \cdot \cos \angle OZP.$$

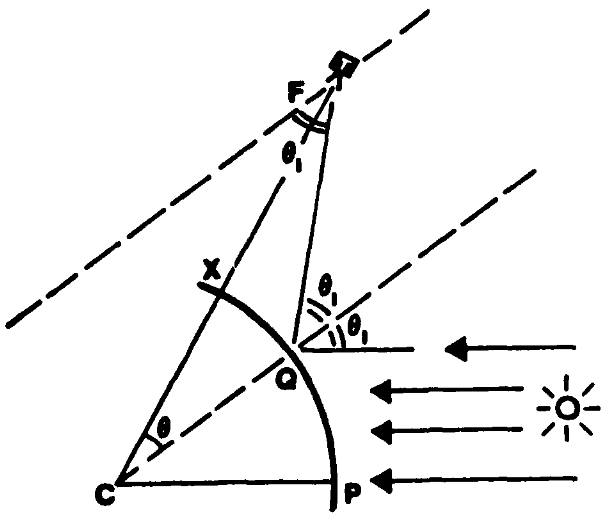
Since $\sin OZ \equiv 1$ and $\cos OZ \equiv 0$,

$$\cos PO = \sin ZP \cdot \cos \angle OZP$$

$$\sin \angle ZPO = \frac{\sin OZ}{\sin PO} \cdot \sin \angle OZP = \frac{\sin \angle OZP}{\sin PO}$$

$$\sin \angle POZ = \frac{\sin ZP}{\sin PO} \cdot \sin \angle OZP = \sin ZP \cdot \sin \angle ZPO.$$





C= Center of the earth

F= Satellite

O= Equator crossing (ascending node)

P= Sub-solar point (SSP)

Q= Primary specular point (PSP)

X= Point on trajectory of satellite subpoint track where arc $\widehat{XP}$ is perpendicular to $\widehat{OX}$

Z= North Pole

θ= Angle sustaining the arc $\widehat{XQ}$

θ_1= Incident angle

Figure 1. Geometrical aspects of determining PSP location in polar-orbiting satellite data.

Consider spherical triangle XPO:

$$\angle OXP \equiv 90°$$

$$\angle POX = \text{satellite inclination angle} - (90° - \angle POZ)$$

$$\sin XP = \sin PO \cdot \sin \angle POX$$

$$\sin OX = \tan XP \cdot \cot \angle POX$$

$$\cos \angle XPO = \cos OX \cdot \sin \angle POX.$$

Consider spherical triangle ZPX:

$$\angle ZPX = \angle ZPO - \angle XPO$$

$$\cos XZ = \cos PX \cdot \cos ZP + \sin PX \cdot \sin ZP \cdot \cos \angle ZPX$$

$$\sin \angle XZP = \frac{\sin PX}{\sin XZ} \cdot \sin \angle ZPX.$$

It can be seen in Figure 1 that the latitude of X = 90° - XZ and that the longitude of X = longitude of SSP + $\angle XZP$. The above sequence provides the basis for determining the arc of XP which will be used in locating Q.

Step 2:

Find the position of the PSP (point Q in Figure 1):

$\overline{CX}$ = radius of the earth $\equiv$ R

$\overline{XF}$ = height of the satellite $\equiv$ H

θ = QX

$\angle PCX$ = PX

θ_I (the incident angle) = $\angle PCX - \theta$.

Consider plane triangle QCF:

$$\angle FQC = 180° - \theta_I$$

$$\angle CFQ = 180° - \angle FQC - \theta = \theta_I - \theta$$

$$\frac{R}{\sin \angle CFQ} = \frac{R + H}{\sin \angle FQC}$$

$$\frac{R}{\sin(\angle PCX - 2\theta)} = \frac{R + H}{\sin(\angle PCX - \theta)} \; .$$

Angle θ or arc QX can be found through iteration of the above equation.

Consider spherical triangle ZPQ:

$$PQ = PX - QX$$

$$\cos QZ = \cos PQ \cdot \cos ZP + \sin PQ \cdot \sin ZP \cdot \cos \angle ZPX$$

$$\sin \angle QZP = \frac{\sin PQ}{\sin QZ} \cdot \sin \angle ZPX .$$

It is obvious from Figure 1 that the latitude of Q = 90°-QZ, and that the longitude of Q = longitude of SSP + $\angle$QZP. Care should be taken in calculating the longitudes of points X and Q because of the changes in longitude designations between the Eastern and Western Hemispheres.

3. SOURCES OF ERROR

Aside from the assumption that the satellite subpoint track is a great circle arc, other sources of error should be considered:

a. The earth itself is not a perfect sphere.

b. The SSP is assumed to remain constant during the satellite pass through the area of sunglint.

c. The satellite inclination angle may vary from orbit to orbit by as much as $\sim\pm 1.5$ because of gravitational influences.

d. The height of the satellite may commonly vary by ± 35 km or more if the satellite is not launched in a perfectly circular orbit. During the approximate 15 min duration of the satellite pass through the area of sunglint, the error contributed by the great circle assumption would give the satellite inclination angle an additional variation of $\pm 2°$. This would contribute, on the average, to a $\pm 1°$ variation in latitude and $\pm .5°$ variation in longitude in estimating the position of the PSP. Considering the uncertainties listed above, the great circle assumption for the satellite subpoint track appears to be quite reasonable.

4. SAMPLE CALCULATION

An actual example and sample calculation are provided to demonstrate the use of this technique in determining the location of the PSP; step-by-step computation is illustrated in Appendix II. Figure 2 is a DMSP satellite image for 22 August 1978. A sunglint pattern east of Hurricane Kristy is very apparent extending northward to the coast of California from the south at the bottom of the image. The satellite inclination angle for this example was assumed to be the normal 98.7°. The longitude of the ascending node for this pass was 113.5°W at 18:55:31 GMT. The latitude of the SSP at this time was 12.0°N and the longitude of the SSP was 103.8°W. As shown in the Appendix II, the latitude of X is estimated to be 10.5°N and longitude to be 115°W. Through the iteration scheme, θ is 1.2°. Finally, the latitude of PSP = 10.7°N and the longitude of the PSP = 113.9°N.

It can be seen in Figure 2 that this point is located under convective cloudiness of the intertropical convergence zone (ITCZ) near the center of the sunglint pattern. Sunglint reflection is not very bright in the region just north of this point, indicating that sea state in that area was not calm, but in fact rather rough, since this area should normally produce the brightest reflection.

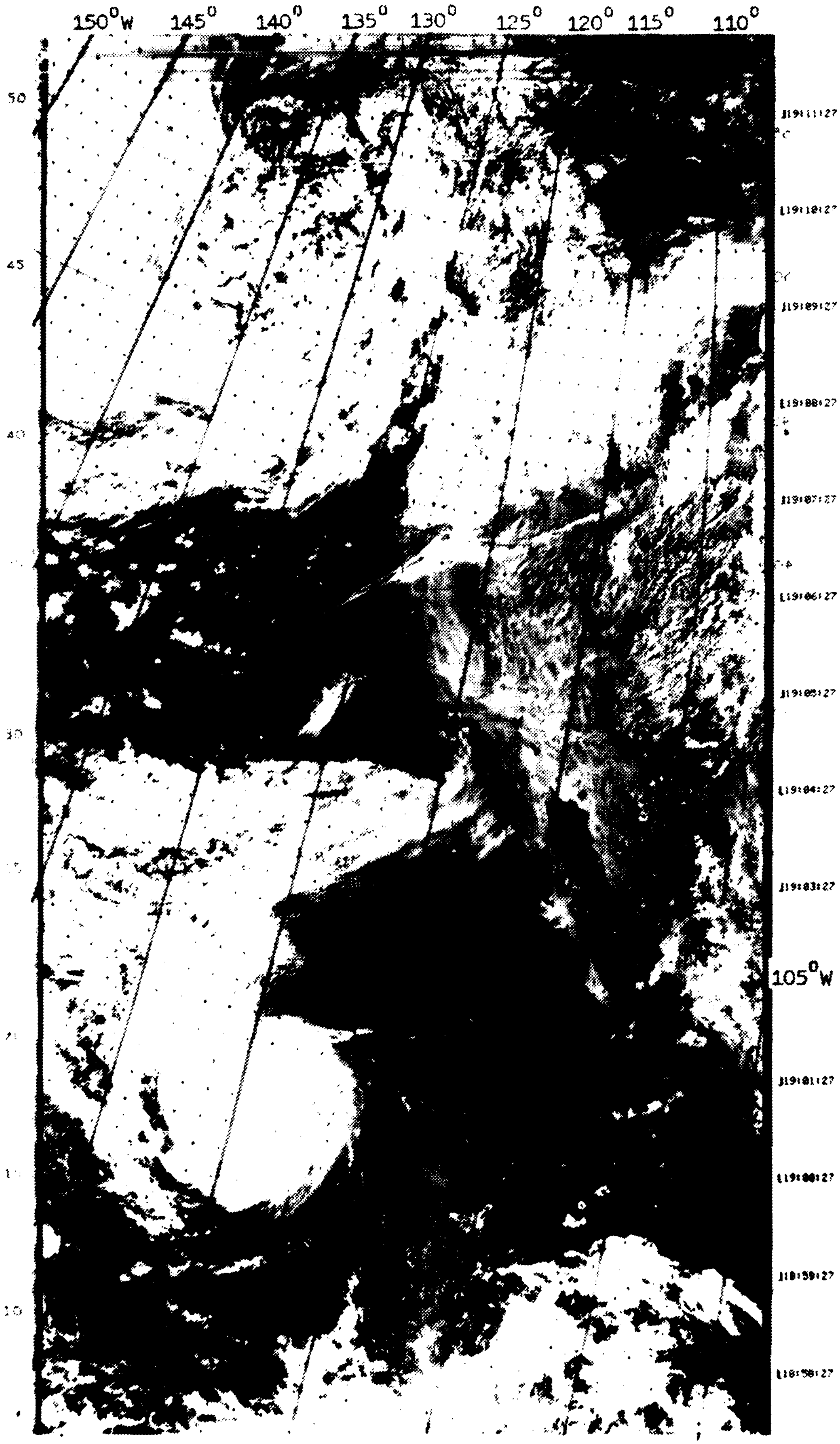


Figure 2. DMSP satellite image for 22 August 1978.

5. SUMMARY

A mathematical procedure for calculating the PSP in polar orbiting satellite data has been described. This procedure can be developed easily into a small computer program that can be run on a minicomputer (e.g., HP-9845) or a programmable calculator (e.g., TI-59); with only a few inputs, the PSP of the sunglint can be located routinely. The procedure provides a quantitative basis for this determination, which will be useful for research purposes and for practical application in field analysis. The computation scheme must be modified, however, if the scheme is to be used to locate the PSP during a satellite's descending pass or during the period when the sub-solar point is west of the satellite subpoint track.

REFERENCE

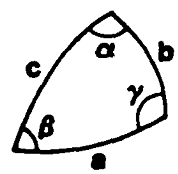
Fett, R. W., and W. Mitchell, 1977: Naval Tactical Applications Guide, Vol. 1: Techniques and Applications of Image Analysis. NEPRF Applications Report AR 77-03, DTIC AD No. B-024-969, 110 pp.

APPENDIX I

LAWS OF SINES AND COSINES

1. The Law of Sines: In any spherical triangle, the sines of the sides are proportional to the sines of the respectively opposite angles:

$$\frac{\sin a}{\sin \alpha} = \frac{\sin b}{\sin \beta} = \frac{\sin c}{\sin \gamma}.$$



2. The Law of Cosines for Sides: In any spherical triangle, the cosine of any side is equal to the product of the cosines of the other two sides plus the product of the sines of those sides times the cosine of their included angle:

$$\cos a = \cos b \cos c + \sin b \sin c \cos \alpha,$$

$$\cos b = \cos c \cos a + \sin c \sin a \cos \beta,$$

$$\cos c = \cos a \cos b + \sin a \sin b \cos \gamma.$$

3. The Napier's Rules for a Right Spherical Triangle:

$$\sin a = \sin c \sin \alpha,$$

$$\sin a = \tan b \cot \beta,$$

$$\sin b = \sin c \sin \beta,$$

$$\sin b = \tan a \cot \alpha,$$

$$\cos c = \cot \alpha \cot \beta,$$

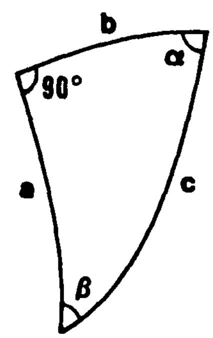
$$\cos c = \cos a \cos b,$$

$$\cos \alpha = \cos a \sin \beta,$$

$$\cos \alpha = \tan b \cot c,$$

$$\cos \beta = \cos b \sin \alpha,$$

$$\cos \beta = \tan a \cot c.$$



APPENDIX II

SAMPLE COMPUTATION PROCEDURES

Before the PSP can be calculated, several background parameters must be determined:

1. Find SD (solar declination angle). This angle can be found according to the day of year in the <u>Smithsonian Tables.</u>

2. Find LN (longitude of equator crossing).

3. Find TN (time of equator crossing). LN and TN usually appear on the satellite image itself.

4. Find LTN (solar longitude). LTN = (TN-12)*15, if TN>12. LTN = (TN-12)*15 + 180, if TN<12.

5. Find SI (satellite inclination angle). This is treated as a constant for a given satellite.

6. Find R (average radius of the earth).

7. Find H (average height of the satellite).

A suggested computation sheet and the actual computation steps for the 22 August 1978 case are provided. Because the style of the computation steps is very similar to that of a computer program or a programmable calculator program, the entire computation scheme can be transformed easily into a program for an available machine. All units for arcs and angles are in degrees.

(Suggested Computation Sheet)

Case: ____________________

Date: ____________________

a. INPUT (Background Parameters)

1. SD =
2. LN =
3. TN =
4. LTN =
5. SI =
6. R =
7. H =

b. Memory Block:

1. sin ZP =
2. cos ZP =
3. sin PO =
4. angle ZPO =
5. sin POX =
6. arc XP = arc PX =
7. sin XP = sin PX =
8. cos XP = cos PX =
9. sin ZPX =
10. cos ZPX =
11. sin PQ =

c. In Spherical triangle ZPO

1. arc ZP = 90 - SD =

   (calculate sin ZP and cos ZP and put them in the memory block)

2. angle OZP = LN - LTN =

3. $\cos PO = \sin ZP \cdot \cos OZP = X =$

$\text{arc } PO = \cos^{-1} X =$

calculate sin PO and put it in the memory block

4. $\sin ZPO = \dfrac{\sin OZP}{\sin PO} = Y =$

angle ZPO (either in first or second quadrant) =

select ZPO and put it in the memory block

5. $\sin POZ = \sin ZP \cdot \sin ZPO =$

angle POZ =

d. In Spherical Triangle XPO

1. angle POX = SI - (90 - POZ) =

calculate sin POX and put it in the memory block

2. $\sin XP = \sin PO \cdot \sin POX =$

arc XP =

calculate cos XP and put sin XP, cos XP, and arc XP in the memory block

3. $\sin OX = \tan XP \cdot \cot POX =$

arc OX =

4. $\cos XPO = \cos OX \cdot \sin POX =$

arc XPO =

e. In Spherical Triangle ZPX

1. ZPX = ZPO - XPO =

calculate sin ZPX and cos ZPX and put them in the memory block

2. $\cos XZ = \cos PX \cdot \cos ZP + \sin PX \cdot \sin ZP \cdot \cos ZPX =$

arc XZ =

3. $\sin XPZ = \dfrac{\sin PX}{\sin XZ} =$

angle XPZ =

4. latitude of X = 90 - XZ =

longitude of X = LTN + XZP =

f. In Plane Triangle FCQ

1. angle PCX = arc PX =

2. Let res be the residual term in the iteration scheme, then res = $\frac{\sin\ (PCX-2\theta)}{\sin\ (PCX-\theta)} - \frac{R}{R + H}$

3. Assume $\theta = \theta_1 =$, $res_1 = \frac{\sin\ (PCX-2\theta_1)}{\sin\ (PCX-\theta_1)} - \frac{R}{R + H} =$

$\theta = \theta_2 =$, $res_2 = \frac{\sin\ (PCX-2\theta_2)}{\sin\ (PCX-\theta_2)} - \frac{R}{R + H} =$

$\theta = \theta_3 =$, $res_3 =$

$\theta = \theta_4 =$, $res_4 =$

$\theta = \theta_5 =$, $res_5 =$

$\theta = \theta_6 =$, $res_6 =$

$\theta = \theta_7 =$, $res_7 =$

. .

. .

. .

$\theta = \theta_n =$, $res_n =$

4. Select θ_k, where the absolute value of res_k is the smallest.

5. arc XQ = $\theta = \theta_k =$

g. In Spherical Triangle ZPQ

1. arc PQ = PX - QX =

   calculate sin PQ and put it in the memory block

2. cos QZ = cos PQ · cos ZP + sin PQ · sin ZP · cos ZPX =

   arc QZ =

3. sin QZP = $\frac{\sin PQ}{\sin QZ}$ · sin ZPX =

   arc QZP =

4. latitude of PSP (point Q) = 90 - QZ =

   longitude of PSP (point Q) = LTN + QZP =

(Suggested Computation Sheet, Data of 22 August 1978)

Case: DMSP Visible

Date: August 22, 1978

a. INPUT (Background Parameters)

1. SD = 12.0
2. LN = 113.5 W
3. TN = 18:55:31Z = 18.92Z
4. LTN = (18.92-12) x 15 = 103.8W
5. SI = 98.7
6. R = 6370 km
7. H = 833 km

b. Memory Block:

1. sin ZP = 0.97814
2. cos ZP = 0.20791
3. sin PO = 0.26556
4. angle ZPO = 140.7
5. sin POX = 0.73135
6. arc XP = arc PX = 11.2
7. sin XP = sin PX = 0.19422
8. cos XP = cos PX = 0.98096
9. sin ZPX = 0.99317
10. cos ZPX =-0.11667
11. sin PQ = 0.17365

c. In Spherical Triangle ZPO

1. arc ZP = 90 - SD = 78.0

   (calculate sin ZP and cos ZP and put them in the memory block)

2. angle OZP = LN - LTN = 113.5 - 103.8 = 9.7

3. cos PO = sin ZP · cos OZP = X = 0.96416

calculate sin PO and put it in the memory block

4. $\sin ZPO = \frac{\sin OZP}{\sin PO} = Y = 0.63447$

angle ZPO (either in first or second quadrant)

= 39.3 or 140.7

select ZPO and put it in the memory block

5. sin POZ = sin ZP · sin ZPO = 0.62060

angle POZ = 38.3

d. In Spherical Triangle XPO

1. angle POX = SI - (90 - POZ) = 98.7 - (90-38.3) = 47.0

calculate sin POX and put it in the memory block

2. sin XP = sin PO · sin POX = 0.19422

arc XP = 11.2

calculate cos XP and put sin XP, cos XP, and arc XP in the memory block

3. sin OX = tan XP · cot POX = 0.18465

arc OX = 10.6

4. cos XPO = cos OX · sin POX = 0.71887

arc XPO = 44.0

e. In Spherical Triangle ZPX

1. ZPX = ZPO - XPO = 140.7-44.0 = 96.7

calculate sin ZPX and cox ZPX and put them in the memory block

2. cos XZ = cos PX · cos ZP + sin PX · sin ZP · cos ZPX

= 0.18179

arc XZ = 79.5

3. $\sin XPZ = \frac{\sin PX}{\sin XZ} = 0.19753$

angle XPZ = 11.4

4. latitude of X = 90 - XZ = 90 -79.5 = 10.5 N

longitude of X = LTN + XZP = 103.8 + 11.4 = 115.2W

f. In Plance Triangle FCQ

1. angle PCX = arc PX = 11.2

2. Let res be the residual term in the iteration scheme,

then $res = \frac{\sin (PCX-2\theta)}{\sin (PCX-\theta)} - \frac{R}{R + H}$

3. Assume $\theta = \theta_1 = 0.9$, $res_1 = \frac{\sin (PCX-2\theta_1)}{\sin (PCX-\theta_1)} - \frac{R}{R + H}$
$= 0.02912$

$\theta \quad \theta_2 = 1.0$, $res_2 = \frac{\sin (PCX-2\theta_2)}{\sin (PCX-\theta_2)} - \frac{R}{R + H}$
$= 0.01845$

$\theta \quad \theta_3 = 1.1$, $res_3 = \frac{\sin 9.0}{\sin 10.1} - 0.88435 = 0.00769$

$\theta \quad \theta_4 = 1.2$, $res_4 = 0.00335$

$\theta \quad \theta_5 = 1.3$, $res_5 = -0.01461$

$\theta \quad \theta_6 = 1.4$, $res_6 = -0.02609$

$\theta \quad \theta_7 = 1.5$, $res_7 = -0.03783$

$\vdots \qquad \vdots$

$\theta = \theta_n =$, $res_n =$

4. Select θ_k, where the absolute value of res_k is the smallest.

5. arc XQ = $\theta = \theta_k = \theta_4 = 1.2$

g. In Spherical Triangle ZPQ

1. arc PQ = PX - QX = 11.2-1.2 = 10.0

   calculate sin PQ and put it in the memory block

2. $\cos QZ = \cos PQ \cdot \cos ZP + \sin PQ \cdot \sin ZP \cdot \cos ZPX$

   $= 0.18493$

   arc QZ = 79.3

3. $\sin QZP = \frac{\sin PQ}{\sin QZ} \cdot \sin ZPX = 0.17549$

   arc QZP = 10.1

4. latitude of PSP (point Q) = 90 - QZ = 90-79.3 = 10.7N

   longitude of PSP (point Q) = LTN + QZP =

   103.8 + 10.1 = 113.9W

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